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Stabilized lasers for advanced gravitational wave detectors

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Abstract

Second generation gravitational wave detectors require high power lasers with more than 100 W of output power and with very low temporal and spatial fluctuations. To achieve the demanding stability levels required, low noise techniques and adequate control actuators have to be part of the high power laser design. In addition feedback control and passive noise filtering is used to reduce the fluctuations in the so-called prestabilized laser system (PSL). In this paper, we discuss the design of a 200 W PSL which is under development for the Advanced LIGO gravitational wave detector and will present the first results. The PSL noise requirements for advanced gravitational wave detectors will be discussed in general and the stabilization scheme proposed for the Advanced LIGO PSL will be described.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Currently a search for gravitational waves is being performed by an international network of large-scale laser-interferometric gravitational wave detectors (LIGO [1], TAMA300 [2], Virgo [3] and GEO 600 [4]). While the data of the first long science runs are being analyzed, upgrades to the long-baseline detectors are planned to improve their sensitivities and scientific reach for astrophysical sources. The Advanced LIGO Project (AdvLIGO) and the Advanced Virgo project aim for sensitivity improvements of approximately a factor of 10. Before entering the advanced detector phase most currently operating detectors will employ intermediate upgrades to enhance the sensitivity by a factor of 2–3 for a long data taking run starting in 2009.

The limiting noise source of these detectors in the high Fourier frequency region is the shot noise in the photo detection process at the interferometer output port. As this noise scales with the square-root of the light power in the interferometer and the gravitational wave signal scales proportional to the power, an increase in circulating power in the interferometer would improve the signal-to-noise ratio. Hence all advanced gravitational wave detectors call for higher laser power to be injected into the interferometer. Limits to the circulating power are set by the thermal handling capability of the interferometer and by the radiation pressure noise imposed on the suspended mirrors, especially at low frequencies. A power level close to 200 W is anticipated for the Advanced LIGO detector. In addition to the high output power the frequency, power and pointing stability of the laser system are important for the success of advanced gravitational wave detectors. To achieve the required stability levels the fluctuations of the unstabilized system (free-running) have to be reduced by up to eight orders of magnitude by means of feedback control systems or passive filtering.

This paper will describe a 200 W high power laser system designed for use in advanced gravitational wave detectors and a laser amplifier system which will be used to increase the injected power of first generation detectors to 35 W in the LIGO case and to 60 W for the Virgo project. The stabilization scheme designed for the Advanced LIGO detector will be discussed with special emphasis on the power stabilization. Finally a novel diagnostic tool will be described which allows one to analyze the free running and stabilized performance of these laser systems.

2. Low noise high power generation

High power lasers with several kW of output power are commercially available. These lasers use topologies like thin disc, slab or fiber geometries in, for example, master-oscillator power-amplifier (MOPA) configurations to generate the high output power and are used for different applications. Unfortunately the purity of the spatial beam profile, the polarization state and the power and frequency fluctuations of these lasers are not adequate for their use as light sources for gravitational wave detectors.

Several concepts have been followed in the past to produce fundamental mode high power radiation with low noise. A common feature of these concepts is that they use a stable low power master laser with low frequency fluctuations. The proposed MOPA systems as well as injection locked high power stages inherit the frequency stability of this master laser. The reduction of thermal induced birefringence and thermal lenses is one of the main design issues in the high power stage. Zig-zagged paths of the optical axis relative to the thermal gradient are used in side-pumped or end-pumped slab amplifier configurations [5, 6] to reduce thermo-optical effects. In fiber amplifiers [7, 8] the absorption length of the pump light is increased by about two orders of magnitude compared to typical crystal length of several cm to reduce thermal loading. And disc lasers or active mirror lasers [9] reduce thermal effects by designing the optical axis to be parallel with the direction of the thermal gradient.

The high power generation part of the laser system that was chosen for the Advanced LIGO PSL is based on an injection-locked oscillator concept [10] with an internal birefringence compensation scheme. Four laser heads are grouped in two pairs, each combined with a quartz rotator and two lenses to form a birefringence compensation unit. In a two-head system it was demonstrated that such a unit can reduce the depolarization loss by a large factor and that the same output power as in nonpolarized operation could be obtained [11]. Figure 1 shows the optical layout of the 200 W laser system. A monolithic non-planar ring oscillator (NPRO) with 2 W output power [12] is amplified by a four-head Nd:YVO laser amplifier [13] to a power level of 35 W. The birefringent nature of Vanadate avoids depolarization losses and

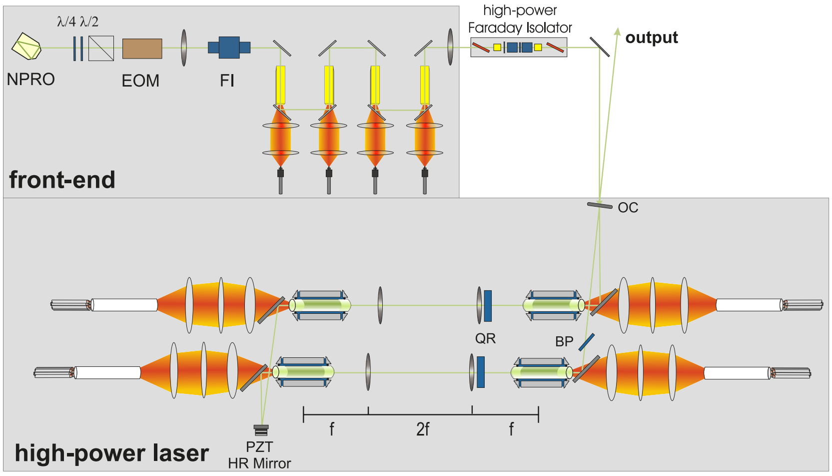

Figure 1. Optical layout of the 200 W laser: The beam from a 2 W NPRO is amplified to 35 W by four Nd:YVO heads and is injected into the high-power slave-cavity which uses two pairs of birefringence compensated end-pumped Nd:YAG rods. The NPRO provides a high frequency stability that is inherited by the high power stage. FI: Faraday isolator, EOM: electro-optical modulator, OC output coupler, BP: Brewster plate, QR: quartz rotator.

power levels of up to 65 W were achieved with a similar amplifier unit when pumped with a 20 W seed laser. The 35 W amplifier output was measured to have a TEM_{00} content of greater than 93% and was operated for several weeks without any significant power loss.

The light from the 35 W stage is then injected into an injection locked Nd:YAG oscillator to produce 200 W of output power. Each Nd:YAG rod is end-pumped by seven fiber-coupled 45 W laser diodes. Each rod has a diameter of 3 mm and its doped region is 40 mm long. They have 7 mm long undoped end caps to reduce thermal loading of the entrance surface. In order to achieve a uniform pumplight distribution and to avoid a transfer of the image of the fiber bundle onto the gain profile fused silica rods are used as pump light homogenizer. A side benefit of these homogenizers is that a diode failure can be compensated by increasing the power of the remaining 6 diodes without changing the pump profile and the gain distribution. A resonator internal Brewster plate is used to ensure linear polarized operation of the system and due to the birefringence compensation described above no significant power drop was observed between unpolarized and polarized operation.

A prototype of the Advanced LIGO high power laser was set up at the Laser Zentrum Hannover (LZH) and a output power of 180 W was achieved. The resonator design was chosen in a way to allow stable operation for only the TEM_{00} mode once the thermal lenses in the laser crystals are developed. By means of the modescan method which is described later in this paper, more than 91% of the linear polarized laser beam was measure to be in the fundamental mode. After a brief warm-up period of 3 min for the pump laser diodes, robust injection locking of the high power oscillator is possible.

The peak-to-peak power fluctuation of the 180 W prototype laser system in a 100 s time interval are below 6%. The spectral density of the relative power fluctuations of the different stages is shown in figure 2. The NPRO noise as well as the noise of the 35 W stage is dominated by the fluctuations of the laser diode driving current. The sources for the additional noise of the 180 W system are not yet identified and are the subject of further investigations.

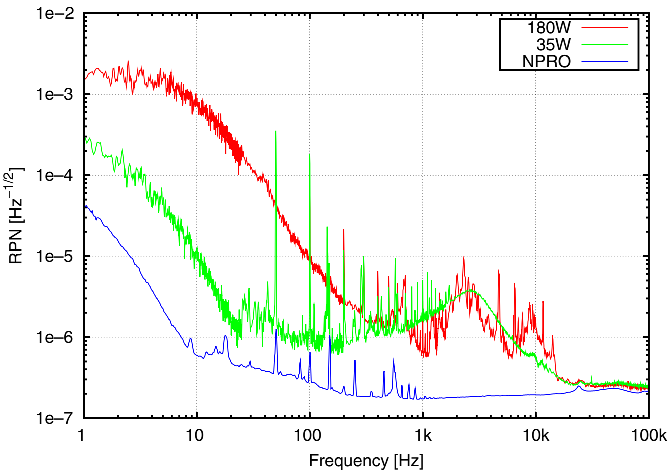

Figure 2. Spectral density of the relative power noise (RPN) of the different stages of the Advanced LIGO PSL prototype.

3. Layout and stabilization of the Advanced LIGO high power laser

As in initial gravitational wave detectors frequency, power and spatial fluctuations of the input light can couple into the gravitational wave channel of advanced detectors. The relevant transfer functions depend strongly on the interferometer layout and on the filtering function of the optical cavities. Even though no general requirements on the laser stability can be set, it is clear that the laser fluctuations in advanced gravitational wave detectors have to be reduced by many orders of magnitude to achieve the design sensitivity. In this section, we will describe a stabilization scheme for the Advanced LIGO PSL. Even though it has features specific for Advanced LIGO it can serve as an example for more general stabilization concepts. The design requirement of the Advanced LIGO PSL is to provide 165 W of power at the interface to the suspended modecleaner with a higher order mode content of less than 5% and with low temporal and spatial fluctuations. Figure 3 shows the anticipated stabilization scheme.

The light of the NPRO is phase modulated by an electro-optical modulator, passes an acousto-optic modulator (AOM) and a Faraday isolator and is then amplified by a single pass through four amplifier heads to 35 W. The NPRO and the amplifier form the so-called front–end which serves as the master laser for the injection-locking scheme of the 200 W oscillator. A Pound–Drever–Hall scheme [14] is used to generate the error signal for the injection locking control loop. The control signal is fed back to a piezo electrical transducer which keeps the length of the slave cavity within the injection locking range of 12 MHz. This control loop has a unity gain frequency of 6kHz. The 200 W beam is then modematched into a rigid-spacer ring-cavity called a premodecleaner (PMC) which is used to spatially filter the laser beam. A length control loop keeps the PMC resonant with the laser field. The PMC will be housed in a sealed enclosure to avoid acoustic coupling to either the beam pointing or to the frequency of the transmitted radiation. A fraction of the beam is split off after the PMC for frequency stabilization purposes. This beam double passes an AOM which is used in the first diffraction order as a frequency shifter and the light is then modematched into a reference cavity. A control loop stabilizes the laser frequency to this cavity by feeding back to the frequency actuators of the NPRO. For frequencies above a few Hz the suspended modecleaner

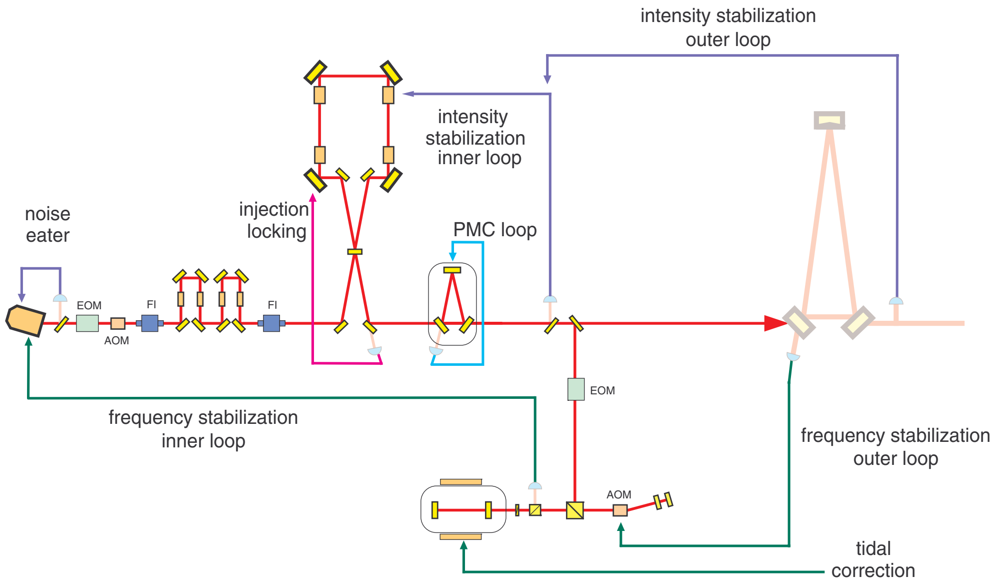

Figure 3. Stabilization scheme of the Advanced LIGO PSL . Control loops are required for the injection locking, the PMC length control, the laser frequency control and for the power noise reduction. The suspended modecleaner (indicated by the shaded cavity on the right) serves as a reference for the outer frequency stabilization loop and a photodiode downstream of it is used as the sensor for the outer power stabilization loop.

of Advanced LIGO will be a more stable frequency reference than the reference cavity. Hence the AOM frequency shifter will be used as an actuator for an outer frequency stabilization loop to stabilize the laser to the modecleaner. Finally a so-called tidal actuator which controls the temperature of the reference cavity is available as an actuator to lock the laser to the slow drift of the interferometer arm cavities caused by the earth tides. This tidal correction scheme will only be used if the common-mode drift of the interferometer arm cavities cannot be compensated by the mirror position control. The frequency control system described is very similar to the one used for the initial LIGO detectors [15] which has already demonstrated that the stability level necessary for Advanced LIGO can be reached.

The power control is split into three sections: the first loop which is often called the noise eater stabilizes the power noise of the NPRO and mainly reduces the fluctuations at the relaxation–oscillation frequency of approximately 1.2 MHz. The second loop senses the noise of the high power laser and feeds back to the AOM placed between NPRO and 35 W stage and to the current of the high power pump diodes. The error signal for the third loop will be generated by sensing the power fluctuations downstream of the suspended modecleaner. The control signal of that loop will be added into the error point of the second loop. The demanding power stability requirements and the best results achieved so far are subject of the next section.

4. Power stabilization

Various coupling mechanisms of laser power fluctuations into the gravitational wave channels exist in advanced detectors [16]. These coupling mechanisms depend strongly on the interferometer design and can be divided into two classes. The first class couples directly via fluctuations in the light power detected on a photodiode, for example due to an intentional or accidental deviation from the dark-fringe operation point. The second class couples via radiation pressure fluctuations into the position of either the interferometer or modecleaner mirrors. Even though the beamsplitter ideally causes the technical power fluctuations injected into the two interferometer arms to be symmetric, an asymmetry in, for example, the optical losses in the interferometer arms can cause a differential arm length change to be produced by laser power fluctuations. (Please note that in this paper we will only treat so-called technical power noise which in contrast to quantum fluctuations can be reduced by classical stabilization schemes and which will be divided equally into both output ports of a beamsplitter.) In the case of the Advanced LIGO detector the strongest coupling of power fluctuations is expected to be caused by the radiation pressure effects in the interferometer arms which might show an asymmetry as high as 1% . This leads to a requirement for the relative power noise (RPN) which is most stringent at 10 Hz Fourier frequency with RPN $\leqslant 2\times10^{-9}\,\mathrm{Hz}^{-1/2}$.

Starting from a free running RPN of approximately $10^{-3}\,\mathrm{Hz}^{-1/2}$ a nested control loop with more than 110 dB loop gain has to be designed. As the free running noise of the 200 W laser at lower frequencies is dominated by the fluctuations of the high power stage, we have to measure the RPN behind the injection locked oscillator. The sensing point is placed downstream of the PMC such that power fluctuations caused by beam pointing or PMC length noise can be detected as well. Several options exist to reduce these fluctuations. The feedback signal could be sent to the AOM placed between the NPRO and the amplifier stage. This actuator has a high bandwidth of up to 100 kHz but has a limited actuation range as the RPN transfer function from the NPRO power to the power of the full system is − 20 dB up to 1 kHz. A second option is to modulate the pump diode power of the high power stage. This actuator has a large range and reduces the noise at the stage where it is introduced. The laser dynamics however determines the useful bandwidth of this actuator due to a transfer function pole at a frequency that corresponds to the inverse of the effective lifetime of the upper laser level. A detailed study of the source of the low frequency noise is required to find the dominant noise sources of the full system. Possible candidates are the power noise of the pump diodes of the high power stage, cooling water driven vibrations of the four oscillator laser heads, alignment fluctuations of the oscillator eigenmode relative to the master laser or relative to optical components or some polarization dynamics due to fluctuations in the depolarization of the YAG crystals. Based on the results of this study and depended on the success in noise source reduction we will then design a power stabilization loop which will probably use both actuators with frequency-dependent control filters. The prestabilized laser is then injected into the suspended modecleaner and a photodiode is used to sense the RPN of the beam transmitted by the suspended modecleaner before it is injected into the main interferometer. Frequency fluctuations and beam pointing relative to the eigenmode and resonance frequency of the modecleaner can couple into RPN at this location. Hence a so-called outer power stabilization loop will be used to reduce the RPN of the light at this point by feeding back into the error point of the inner loop.

It has been shown by several groups [17, 18] that the detection of power fluctuations at the RPN $\leqslant 2\times10^{-9}\,\mathrm{Hz}^{-1/2}$ level is problematic. As the main challenge lies in the noise sensing and not in the control loop design, we set up a NPRO power stabilization experiment. With extreme care in the design of the electronics and the optical setup we were able to achieve a RPN level of better than RPN $\leqslant 4\times10^{-9}\,\mathrm{Hz}^{-1/2}$ between 50 Hz and 1.5 kHz [19]. For frequencies above 100 Hz the stability achieved is consistent with a RPN level of RPN $\leqslant 3\times10^{-9}\,\mathrm{Hz}^{-1/2}$ for the stabilized light beam. At frequencies below 100 Hz however we see some excess noise above shot noise. We investigated a number of effects that could produce the additional noise in the light sensing. Some examples are the pointing of the beam on the photodiode in combination with photodiode non-uniformities, polarization fluctuations in combination with a polarization-dependent splitting ratio of the pick-off mirror, scattered light with a fluctuating phase that beats with the main beam under investigation and electronic noise. New investigations indicate that $1/f$ electronic noise is responsible for the excess noise seen at low frequencies. This noise depends on the photocurrent drawn and is hence different from the dark noise of the photodetector. Experiments are underway to test different resistors and InGaAs photodiodes for their $1/f$ noise and to design a low noise photodetector to be used in the outer power stabilization loop.

5. Characterization of the laser fluctuations and of the spatial laser profile

Spatial fluctuations of the laser beam are important noise sources in gravitational wave detectors. It is common to distinguish between deviations from a fundamental Gaussian mode described by the higher order mode content and so-called beam pointing which describes a mismatch of the beam propagation axis from a desired one. As no commercial devices are available to measure these beam parameters with sufficient accuracy, we developed a diagnostic tool [20] to characterize the laser during the development and test phase as well as finally during its operation in the gravitational wave detector. This so-called diagnostic breadboard consists of a rigid spacer Fabry–Perot cavity, the eigenmode of which serves as a spatial reference. A length control system is used to keep the cavity on resonance with the incoming laser beam and an automatic alignment system ensures an optimal beam steering of the laser under test into this cavity. The error and control signal of this alignment control loop can be used to measure the beam-pointing spectral density and the length control loop provides information of the laser frequency noise. The relative power noise can be measured with an InGaAs photodiode which has a bandwidth of 50 MHz and shows shot noise limited performance for 50 mA of photocurrent. Furthermore the automatic alignment system allows for fast turn around times between laser alignment corrections and measurements of its higher order mode content. After an intentional or accidental change of the laser alignment, or simply to control the laser during normal operation the length control and the automatic alignment system is engaged for a couple of seconds to ensure an optimal steering of the beam into the cavity. Then the length and alignment control is switched off and the length of the cavity is scanned over several free spectral ranges. The light power transmitted by the cavity is monitored with a photodiode and recorded by a computer. An analysis program then identifies the fundamental and the higher order modes and determines their relative strength by a fitting algorithm. Figure 4 shows a modescan of the 180 W laser prototype. The three curves show the measurement of the normalized transmitted light power, a fit including higher order modes and a fit of the fundamental mode only. The fraction of the light power in the fundamental mode was determined to be higher than 91%.

This beam diagnostic tool has been proven to be very useful during the laser development, for quality assurance tests and will be an integral part of each Advanced LIGO PSL for *in situ* beam diagnostics.

6. Summary and outlook

In this paper, we described a 200 W prestabilized laser system which is under development for use in advanced gravitational wave detectors. A Nd:YVO amplifier stage was chosen to generate an intermediate power level and an injection-locked oscillator with birefringence compensation was chosen for the high power stage. We used the stabilization scheme of

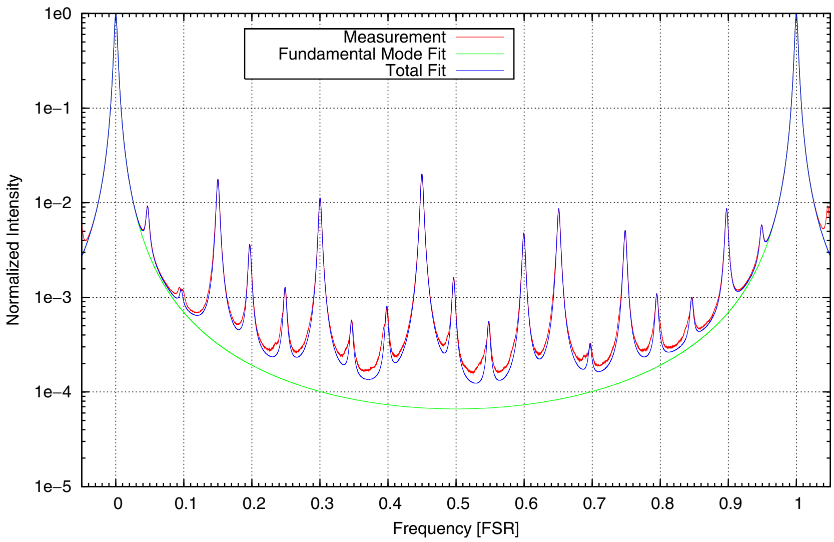

Figure 4. Modescan of the 180 W laser prototype: The laser beam is modematched into a Fabry–Perot ring cavity the length of which is scanned over a free spectral range (FSR). The curves show measurement of the normalized transmitted light power, a fit including higher order modes and the fundamental mode content only which was determined to be higher than 91%.

the Advanced LIGO PSL as an example to introduce possible stabilization concepts. The power noise reduction was identified as the most challenging stabilization task in the PSL. We achieved a shot noise limited RPN $\leqslant 4\times10^{-9}\,\mathrm{Hz}^{-1/2}$ for higher frequencies and the limiting noise source at low f was identified. Finally we presented a modal analysis of a 180 W laser prototype performed with a new diagnostic tool which allows us to characterize the spatial as well as the temporal fluctuation of a laser beam during the laser development and during operation.

The laser requirements for third generation gravitational wave detectors strongly depend on the interferometer design. Higher output power might be required to increase the shot noise limited sensitivity at high frequencies or to reduce the finesse of the arm cavities or the power recycling cavity. A different laser wavelength might by required if for example silicon is used as the test mass material. The power stabilization requirement will most probably become more stringent to reduce the noise caused by radiation pressure fluctuations. Hence more research is required to explore different options for light sources for future gravitational wave detectors and their stabilization.

Acknowledgments

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